AD-A270 474

AL-TR-1993-0016

ARMSTRONG LABORATORY

# QUANTITATIVE FIT EVALUATION OF THREE POTENTIAL INFLIGHT FIRE FIGHTING RESPIRATORY PROTECTION SYSTEMS


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August 1993

Final Technical Report for Period 1 January 1992 - 15 April 1993

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This report has been reviewed and is approved for publication.

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# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



**1. AGENCY USE ONLY** *(Leave blank)*

**2. REPORT DATE**
August 1993

**3. REPORT TYPE AND DATES COVERED**
Final 1 January 1992 - 15 April 1993

**4. TITLE AND SUBTITLE**
Quantitative Fit Evaluation of Three Potential Inflight Fire Fighting Respiratory Protection Systems

**5. FUNDING NUMBERS**
PE - 62202F
PR - 2729
TA - 03
WU - 28

**6. AUTHOR(S)**
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**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
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**8. PERFORMING ORGANIZATION REPORT NUMBER**
AL-TR-1993-0016

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

**11. SUPPLEMENTARY NOTES**

**12a. DISTRIBUTION/AVAILABILITY STATEMENT**
Approved for public release; distribution is unlimited.

**12b. DISTRIBUTION CODE**

**13. ABSTRACT** *(Maximum 200 words)*
The Military Airlift Command (MAC) is considering procurement of the Scott 802300-11 Emergency Escape Breathing Device for individuals combating inflight aircraft fires. Testing by the Federal Aviation Administration found that personnel with neck circumferences of 325 mm (13 in.) or less were not adequately protected by the Scott system. A request was made to independently determine its protection level. This request was done in a comparative quantitative fit evaluation including use of two other respirator systems, the Scott 802300-14 and the Sierra firefighter mask. Based on results of this evaluation, the Scott 802300-14 provided the best overall protection against fumes. Neck size may be a concern for this system but cannot be quantified without the evaluation of more subjects.

**14. SUBJECT TERMS**

| | |
|---|---|
| Aircraft fires | Quantitative fit testing |
| Escape respirator | Scott 802300-11 |
| Fire escape protection | Smoke respirator |

**15. NUMBER OF PAGES**
36

**16. PRICE CODE**

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| Unclassified | Unclassified | Unclassified | UL |

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z39-18
298-102

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# QUANTITATIVE FIT EVALUATION OF THREE POTENTIAL INFLIGHT FIRE FIGHTING RESPIRATORY PROTECTION SYSTEMS

## INTRODUCTION

Fires in the interior of Military Airlift Command (MAC) aircraft during flight are not common, but must be extinguished immediately if one should occur. The most common "injury" suffered during fires of any sort is smoke inhalation. Therefore, individuals who combat aircraft fires require respiratory protection from the smoke and toxic fumes of the fire. Personnel evacuating an aircraft during a fire may also require respiratory protection.

One mask system that MAC is considering buying to fulfill this protection role is the Scott 802300-11 Emergency Escape Breathing Device (11 EEBD) (Fig. 1). Federal Aviation Administration (FAA) personnel determined during 11 EEBD testing that persons with neck circumferences of 325 mm (13 in.) and less were not adequately protected by the system. This discrepancy prompted MAC to request the Armstrong Laboratory (AL) to conduct additional, independent testing of the 11 EEBD to determine whether there actually is a problem for persons with small necks and what levels of protection could be expected with the 11 EEBD.

The 11 EEBD was originally developed as a shipboard escape system for U.S. Navy use. This breathing device is a double hood system that uses a neckdam. The 11 EEBD consists of Teflon Coated Fiberglas Cloth underhood with a Kynol® fabric overhood and a neckdam constructed of 0.075 mm (0.003 in.) polyurethane film (Fig. 2). The system has a "neckpack" mounted in the back of the hood that contains a solid-state oxygen generator (good for 15 min of operation) and a carbon-dioxide ($CO_2$) scrubber (Fig. 3). During normal operation the oxygen ($O_2$) generator supplies 5 lpm of 100% $O_2$ passing through a venturi nozzle. The acceleration in $O_2$ flow rate is used to pull 55 lpm of air from the hood through the $CO_2$ scrubber to be returned to the hood free of $CO_2$ so that it may safely be reused. A complete flow schematic is provided in Figure 4.

Because of the limitations of quantitative fit testing, a mask was needed to act as a basis of comparison. The Sierra firefighter mask (Fig. 5) was chosen for this purpose. The firefighter mask is a full-face seal mask which is connected via a regulator to a compressed air tank. The mask comes in only one size and relies upon an adjustable head harness and a constant air flow to maintain protection.

The test had two objectives: (1) to compare the 11 EEBD to the Sierra firefighter mask (the 14 EEBD mask was added later) and determine relative protection capabilities, and (2) to determine whether persons with necks smaller than 325 mm could safely use the 11 EEBD.

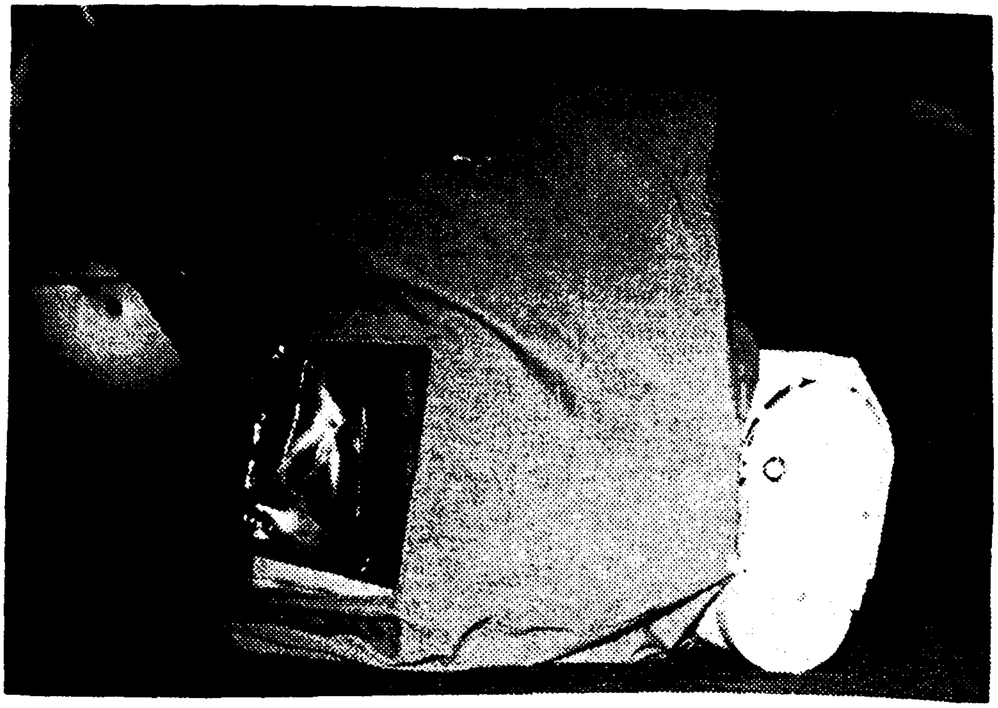

Figure 1. Scott 802300-11 emergency escape breathing device (side view).

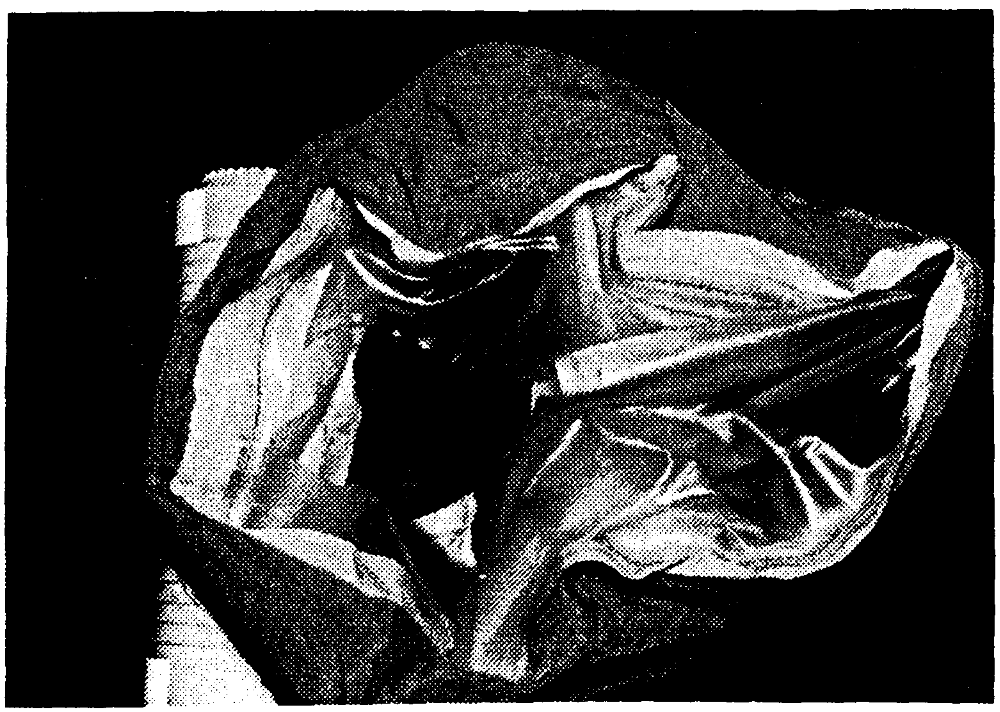

Figure 2. Scott 802300-11 neckdam.

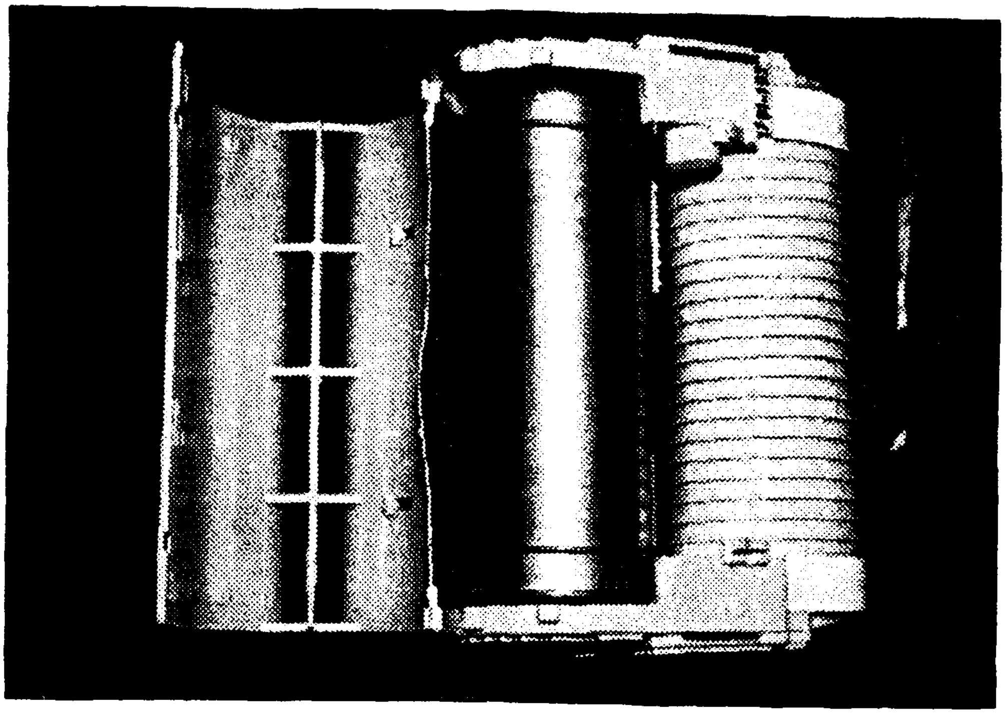

Figure 3. Neckpack from a Scott 802300-11 EEBD (cover removed).

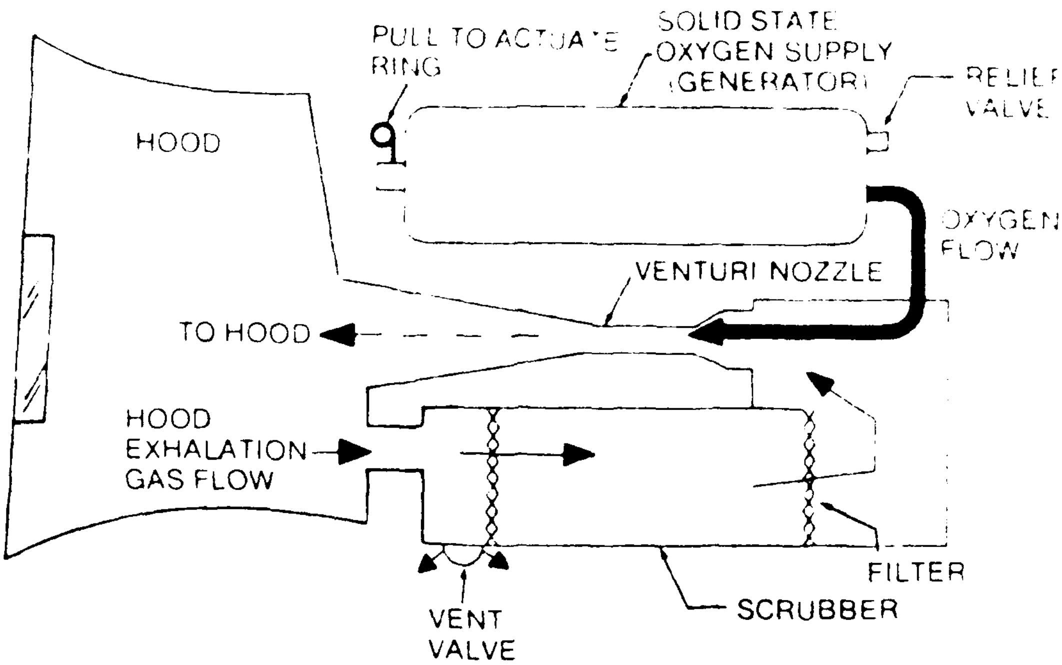


Figure 4. Scott EEBD schematic with air flow paths.

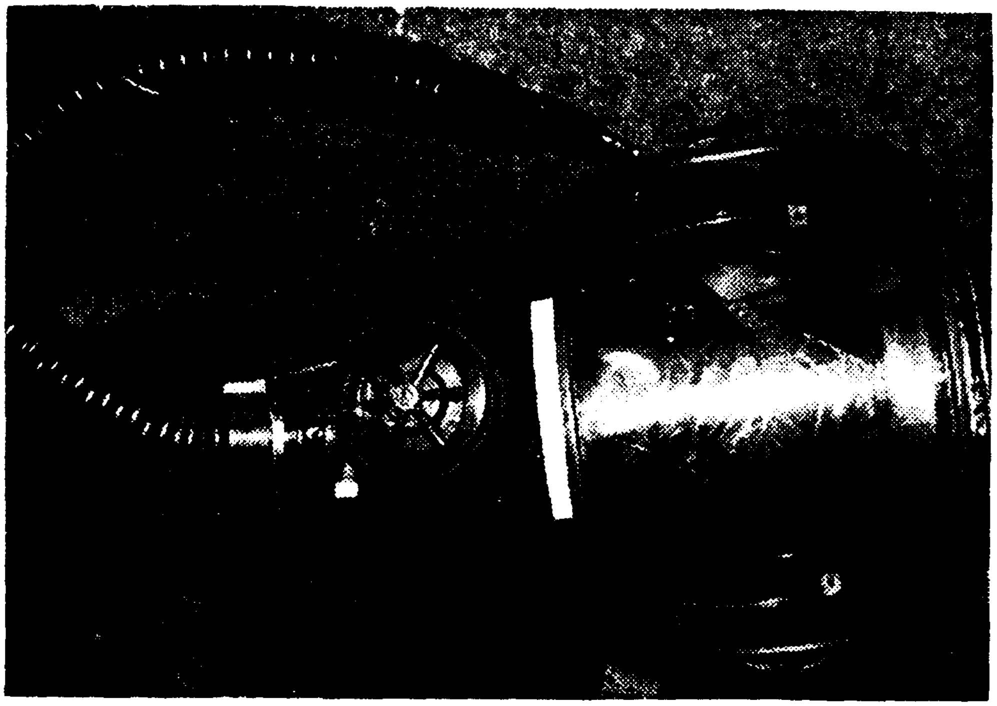

Figure [illegible]. Sierra firefighter mask.

## TEST PROCEDURES

The 11 EEBD system was tested using the AL salt fog quantitative fit testing (QnFT) system. MAC provided the 11 EEBDs and 2 Scott firefighter masks for the testing. Additionally, Scott Aerospace requested that we test the improved version of the 11 EEBD, the 802300-14 Emergency Escape Breathing Device (14 EEBD). MAC agreed. The difference between the 11 EEBD and the 14 EEBD is that the neckdam of the 14 EEBD is constructed of 1.5625 mm (0.06 in.) neoprene.

The AL salt fog QnFT system uses a dry salt aerosol (0.28 μm mass median diameter and a 20 mg $m^{-3}$ concentration). Sampling pumps are set to collect a continuous 3.0 lpm sample from inside both the mask system being tested and the exposure booth. Salt concentrations are determined using flame photometry. A description of the operation of the salt fog system may be found in USAFSAM-TR-81-22*, Sodium Chloride Respirator Fit Test Instrument.

Nineteen subjects, including eight females, participated in the evaluation. No subject had a beard, and four subjects wore glasses. None of the subjects who wore glasses did so while wearing the firefighter mask, but two did while wearing the EEBDs.

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*Koiesar, Edward S., Jr., and Colette M. de la Barre. Sodium chloride respirator quantitative fit test instrument. USAFSAM-TR-81-22, November 1981.

Neck sizes ranged in circumference from 278 mm (11.2 in.) to 415 mm (16.6 in.). All eight female subjects had neck circumferences smaller than 325 mm. A complete listing of subjects and their anthropometric measurements may be found in Appendix A. A "pass/fail" fit factor of 10 was chosen arbitrarily, without objection from MAC or Scott Aerospace.

Fit factor is a measure of mask protection. The fit factor is the dimensionless ratio of a contaminant outside the mask to the amount of contaminant inside the mask. In laboratory tests such as this, the contaminant is a simulant, in this case, sodium chloride aerosol.

The EEBDs and the firefighter masks had to be modified to allow a sample probe to be placed inside the mask cavity. Since the presence of pure $O_2$ causes a false low reading on the salt fog QnFT system, the EEBDs' $O_2$ generators could not be used and the EEBDs were modified further to simulate the $O_2$ generation. Additionally, since the $O_2$ flow also provides the motive force to pull air from the hoods through the $CO_2$ scrubbers, an alternative solution to withdrawing air from the hoods was also necessary.

## EEBD Modifications

To accomplish the EEBD modifications the two end caps on the neckpack were removed. Beneath these two caps are cavities (Figs. 6 and 7). On one side (the inlet side) the $O_2$ and air from the scrubber normally pass though the venturi nozzle and then enter the hood. The end of the $CO_2$ scrubber was capped with a rubber gasket, and the end cap replaced with one that had been modified with a bulkhead fitting. From here, a tee fitting led to two different lines, one to the blower being used to pull air from the hood, and one leading to the mask testing panel.

Bottled compressed air was supplied to the EEBDs. Air to the EEBDs was controlled by a valve set so that the flow was a constant 55 lpm.

The blower pulled 35 lpm from the EEBD hoods which was exhausted into the exposure booth. In addition, sampling removed 3 lpm, for a total of 38 lpm of air removed from the hoods. During normal operation there is a +5 lpm differential between the amount of air ($O_2$) added to the hood and the air removed from the hood. This excess air is exhausted through the neckdam seal.

In setting up the experimental conditions for this evaluation, the primary concern was that no strains be imposed on the system beyond those of normal use. This concern was more important than duplicating the normal operating flows of the EEBDs (60 lpm inlet and 55 lpm scavenging). In the test conditions described earlier there is a difference of 17 lpm between the 55 lpm inlet flow and 38 lpm outlet flow; 12 lpm greater than the normal 5 lpm difference. The greater difference between inlet and outlet was necessary because the 5 lpm flow of pure $O_2$ from the

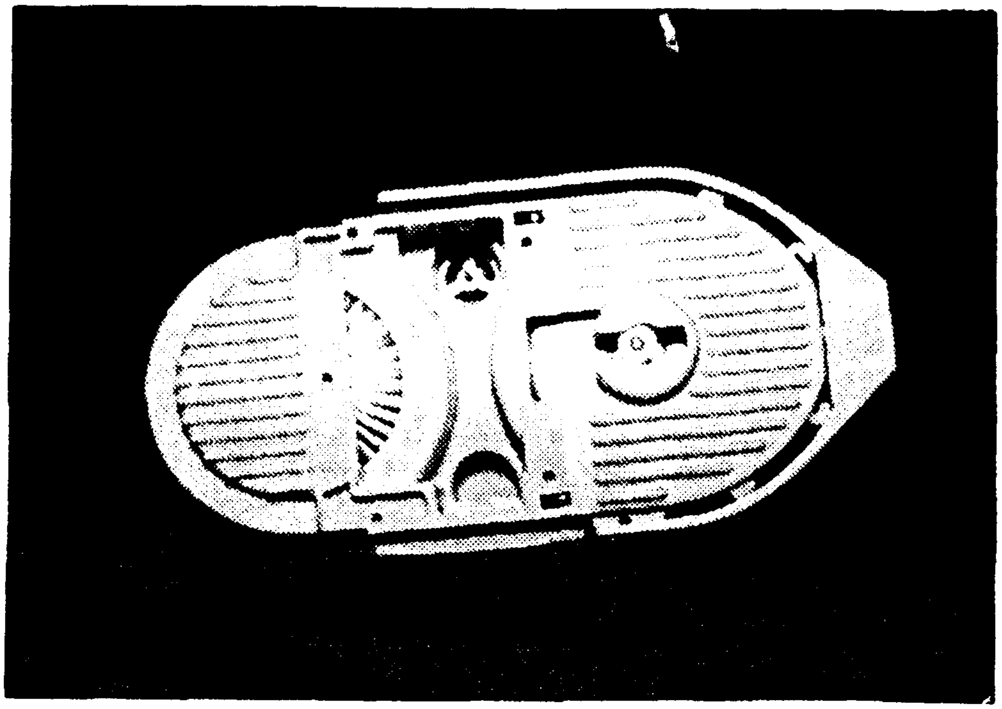

Figure 6. Outlet cavity (showing hood interface).

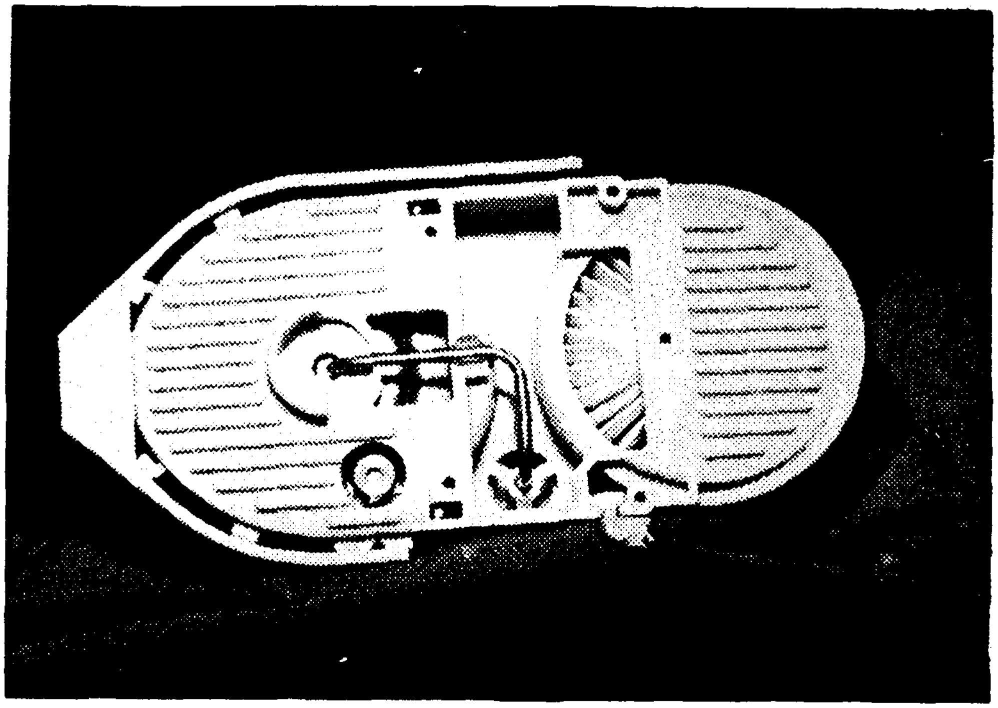

Figure 7. Inlet cavity (showing venturi entrance).

solid state generator had been replaced by normal air. The decrease in $O_2$ content would result in increased subject ventilation, placing a greater demand on the system. The increased difference between inlet and outlet flows compensated for this decreased $O_2$ effect.

### Firefighter Mask Modification

The firefighter mask was modified for the experiment by the insertion of an AL developed probe between the air hose and the mask. This probe allows a sample to be taken from the interior of the mask without destroying the mask. The probe design provides for minimum interference with normal mask operation. Bottled compressed air was supplied to the firefighter masks through a firefighter regulator (the flow was not measured).

### Test Protocol

A six "exercise" test protocol was used. The six exercises were (in the order performed): (1) normal breathing, (2) deep breathing, (3) moving the head from side-to-side, (4) moving the head up-and-down, (5) reading a paragraph out loud, and (6) facial grimacing. Each exercise was performed for 30 s. Fit factors for each individual exercise are reported as well as an overall fit factor. The overall fit factor is derived from the reciprocal of the arithmetic average for the six exercises. The equation describing the derivation (a harmonic mean) is:

$$F_o = 6/[(1/F_1)+(1/F_2)+(1/F_3)+(1/F_4)+(1/F_5)+(1/F_6)]$$

where: $F_o$ = overall fit factor

$F_1$ = fit factor of the first exercise, etc.

## RESULTS

The overall fit factors for the individual subjects are given in Appendix A along with the neck circumference data. Fit factors for individual masks and individual exercises are given in Appendixes B through D.

To analyze the data statistically, a log base 10 transformation is used. Nonparametric testing results show that the log-normal assumption is sufficiently close.

### Ranking and Significance

Mean and median values for the overall fit factor are given in Table 1. Both two-way analysis of variance (ANOVA) and Duncan's multiple range tests show the mask worn to be a significant factor in three of the exercises, borderline for one, and significant for the overall fit factor. In all cases where there is significance, the 14 EEBD is better than the firefighter mask. There is only one exercise where the 11 EEBD is significantly better than the firefighter mask, and in no case are

the 11 EEBD and 14 EEBD significantly different. However, there is a consistent ranking of mean and median values, with the 14 EEBD getting the highest fit values, followed by the 11 EEBD, and the firefighter mask getting the lowest values.

**Table 1. Fit Factor Means and Medians of the Test System**

| Masks | Mean (log base 10) | Mean (natural) | Median |
|---|---|---|---|
| 11 EEBD | 1.6346 | 43 | 37 |
| 14 EEBD | 1.9395 | 87 | 47 |
| Firefighter | 1.3151 | 21 | 14 |

Examining the distribution of results by powers of ten (Table 2 and the histograms in Figs. 8 through 14), the differences between systems by fit factors are more apparent. The ranking of the three systems by fit factors is the 14 EEBD, the 11 EEBD, and finally the firefighter mask.

**Table 2. Distribution of Test Population by Fit Factor Order of Magnitude**

| | 11 EEBD | 14 EEBD | Firefighter |
|---|---|---|---|
| $10^0$ | 6 | 2 | 6 |
| $10^1$ | 8 | 9 | 8 |
| $10^2$ | 3 | 5 | 5 |
| $10^3$ | 2 | 3 | - |

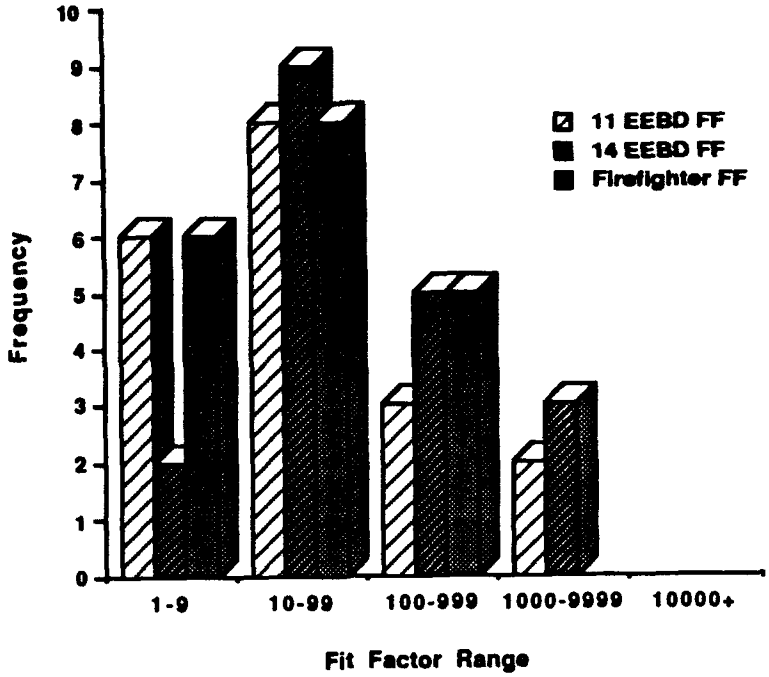


Figure 8. Distribution of fit factors.

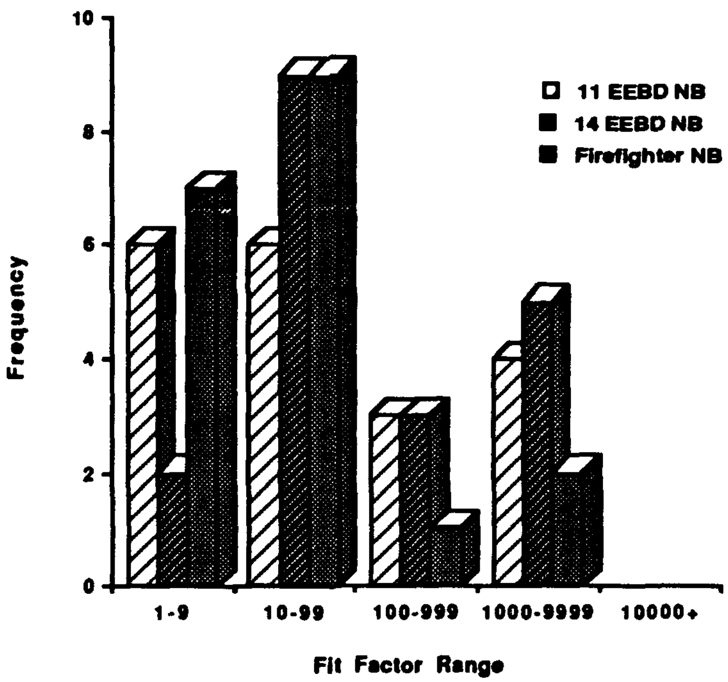


Figure 9. Distribution of normal breathing fit factors.

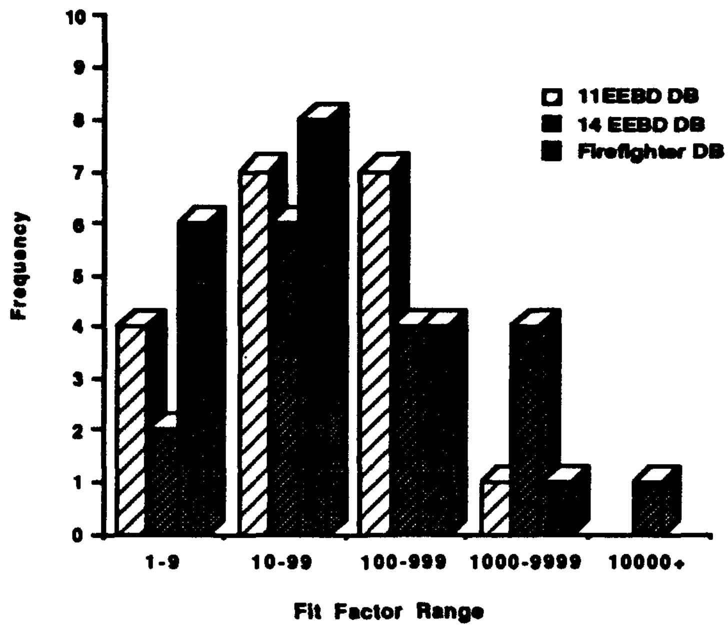


Figure 10. Distribution of deep breathing fit factors.

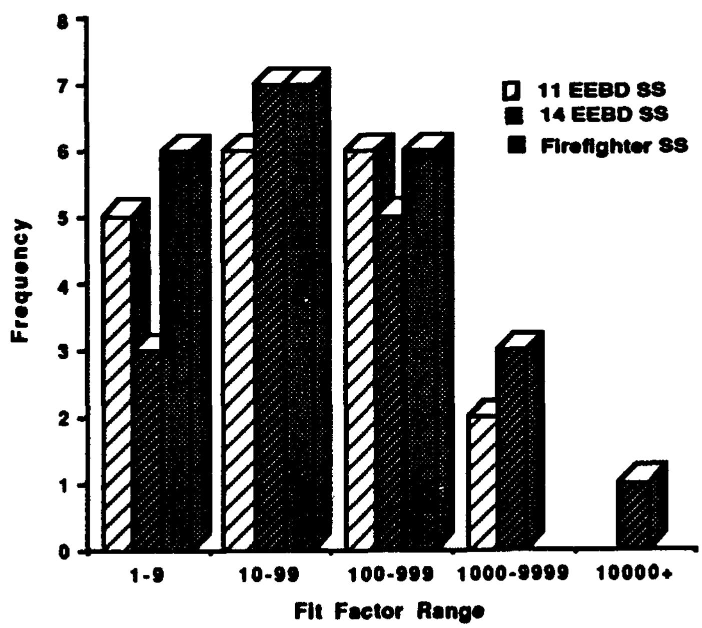


Figure 11. Distribution of head side-to-side fit factors.

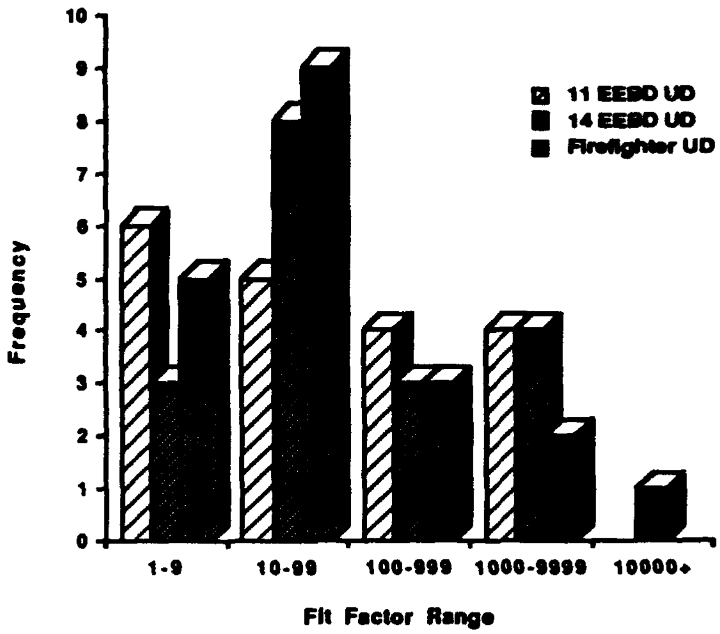


Figure 12. Distribution of head up-and-down fit factors.

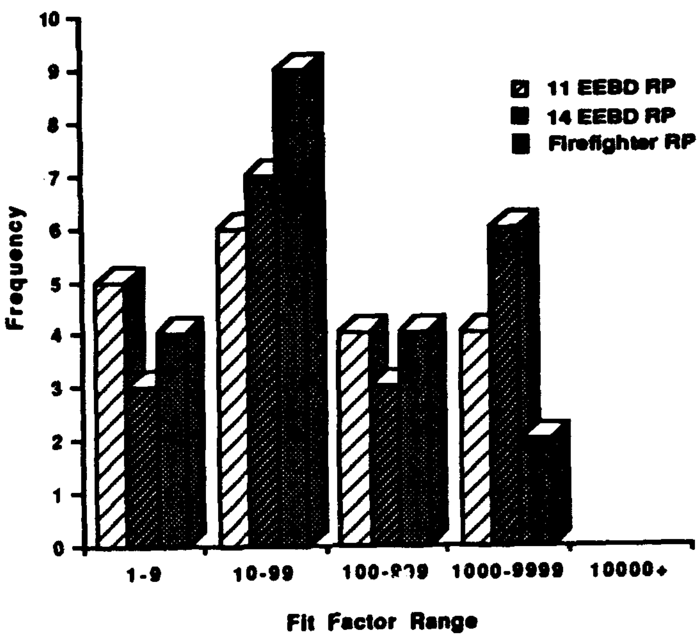


Figure 13. Distribution of read the paragraph fit factors.

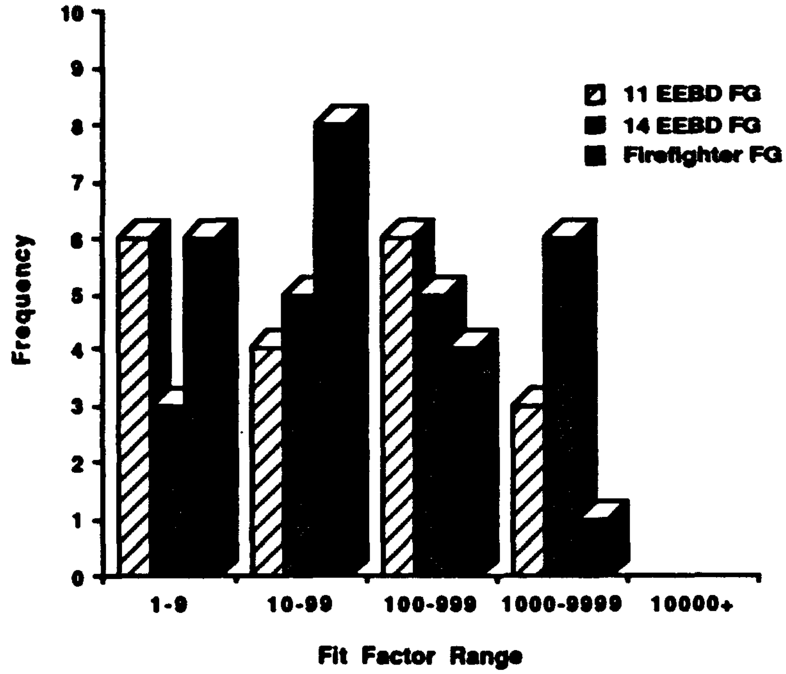


Figure 14. Distribution of facial grimacing fit factors.

## Order Effects

The test protocol called for varying the order in which the masks were worn during the test to not affect test results. Statistics were used to confirm this order. Three subject groups wore the masks in the following order: group one, 11 EEBD, 14 EEBD, firefighter; group two, 14 EEBD, firefighter, 11 EEBD; and group three, firefighter, 11 EEBD, 14 EEBD. In no case were the results from any particular group significantly different from any other group's, and by mask and group a significant difference was found for only one exercise, head side-to-side. Since only one significant example of mask by group difference was found, we concluded that the mask order did not affect the test.

## Neck Size Effects

The effect of neck circumference on the test results for the 11 and 14 EEBDs was also examined (NOTE: Neck circumference is not a factor for the firefighter mask.) since this was a concern based upon the results of the early FAA test of the 11 EEBD. It is important to note that the factors affecting performance of the neck seal masks, are not clearly understood and have never been rigorously examined. (Similarly, few conclusions have been made about the performance of face seal masks with respect to anthropometrics and other factors.) Having worked with a variety of neck seal masks, we suspect the following factors affect neck seal mask performance: neck circumference, the size and rigidity of the neck tendons, Adam's apple size and mobility, and the

amount of hair on the neck. Of these four factors, only the first one, neck circumference, has been quantified at all.

Generally the shape of the curve comparing fit factor to neck circumference for a neckdam sized for the 50th percentile member of the population will be an inverted bathtub curve. Between a certain range of sizes the neckdam will perform relatively the same, taking into account individual differences in head movement and breathing patterns. Below a certain neck size, the neckdam loses effectiveness, and there is a similar effect for very large necks. This pattern is true for well fitting neckdams. The other three factors mentioned earlier have not been examined and are the results of informal observations taken during fit tests of neck dam systems. All of these observations (neck circumference effect included) have been for negative pressure systems. Systems using blown air with airflows greater than 3 cubic feet per minute in conjunction with neckdams have had consistently high levels of protection.

Figure 15 is the scatterplot of protection versus neck circumference for the 11 EEBD and the overall fit factor; Figure 16 illustrates the 14 EEBD. The plots for the individual exercises may be found in Appendixes E and F. These plots show no clear relationship between neck circumference and protection. Of the eight subjects with neck sizes smaller than 325 mm, three had protection levels less than 10 for the 11 EEBD where one was less than 10 for the 14 EEBD. There was one subject with a very large neck (greater than 400 mm) who also scored consistently low with both the 11 and 14 EEBDs. However, it is important to note that of the number of protection failures (a fit factor less than 10), the percentage of subjects with neck circumferences less than 325 mm or greater than 400 mm was always 66% or greater. Though the number of subjects for this experiment was not high enough to prove statistical significance, it appears that subjects with small necks run a greater risk of mask protection failures than subjects with mid-range sized necks and that using the 14 EEBD can reduce this risk to a great extent.

## CONCLUSION

Based on the results of this evaluation, it appears that none of these masks will provide all personnel adequate protection in case of exposure to toxic fumes. In terms of fit factor, the best of the systems tested is the 14 EEBD. Neck size appears to be of some concern for this system, but to determine the actual quantitative seriousness of this concern would need re-evaluation using a panel with a greater number of subjects.

A need identified by this study is a standard for determination of required protection levels. No standard was provided by MAC or Scott Aerospace for this test and the choice of a pass/fail fit factor of 10 was arbitrary on the part of the investigators. It is recommended that more definitive sets of standards be developed.

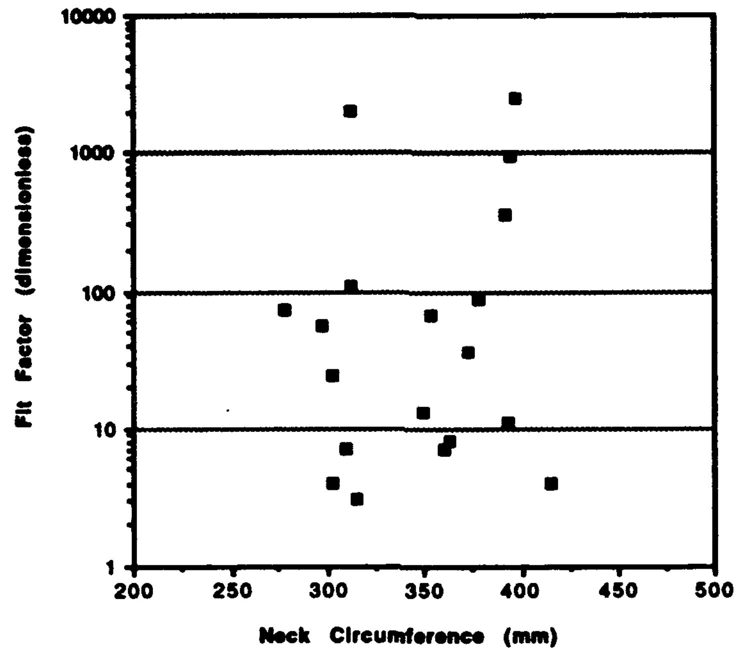


Figure 15. Fit factor versus neck circumference for the 802300-11 EEBD.

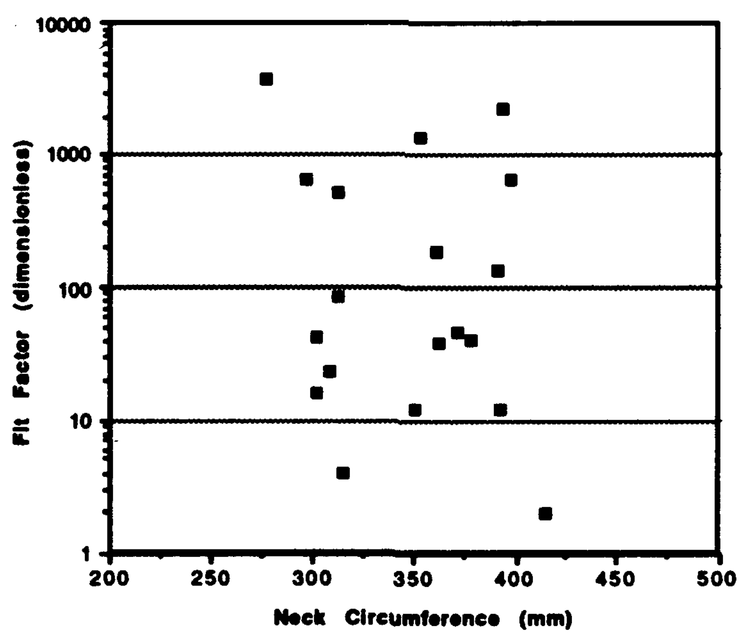


Figure 16. Fit factor versus neck circumference for the 802300-14 EEBD.

## Appendix A

## SUBJECT FIT FACTOR AND NECK CIRCUMFERENCE DATA

| | Fit Factor | | | |
|---|---|---|---|---|
| Subject | 11 EEBD | 14 EEBD | Firefighter | Neck Circumference (mm) |
| 1 | 89 | 40 | 166 | 378 |
| 2 | 365 | 135 | 3 | 391 |
| 3 | 2,054 | 517 | 367 | 312 |
| 4 | 7 | 23 | 7 | 309 |
| 5 | 4 | 16 | 16 | 302 |
| 6 | 37 | 47 | 23 | 372 |
| 7 | 4 | 2 | 14 | 415 |
| 8 | 3 | 4 | 14 | 315 |
| 9 | 11 | 12 | 262 | 393 |
| 10 | 2,546 | 648 | 11 | 398 |
| 11 | 13 | 12 | 24 | 350 |
| 12 | 66 | 1,370 | 2 | 353 |
| 13 | 74 | 3,812 | 898 | 278 |
| 14 | 8 | 39 | 18 | 363 |
| 15 | 111 | 85 | 2 | 312 |
| 16 | 55 | 647 | 2 | 297 |
| 17 | 7 | 185 | 2 | 360 |
| 18 | 24 | 42 | 35 | 302 |
| 19 | 944 | 2,259 | 168 | 394 |

## Appendix B

### FIT FACTOR BY SUBJECT AND EXERCISE FOR THE 11 EEBD

| | Exercise | | | | | |
|---|---|---|---|---|---|---|
| Subject | NB | DB | SS | UD | BP | FG |
| 1 | 46 | 205 | 101 | 55 | 151 | 156 |
| 2 | 200 | 273 | 317 | 930 | 1,072 | 383 |
| 3 | 4,787 | 881 | 1,390 | 3,225 | 2,871 | 5,008 |
| 4 | 4 | 18 | 12 | 5 | 5 | 76 |
| 5 | 9 | 8 | 7 | 6 | 5 | 3 |
| 6 | 18 | 38 | 14 | 100 | 19 | 63 |
| 7 | 4 | 4 | 9 | 8 | 2 | 6 |
| 8 | 5 | 2 | 3 | 4 | 2 | 5 |
| 9 | 16 | 10 | 21 | 15 | 8 | 7 |
| 10 | 1,378 | 1,225 | 6,463 | 6,040 | 4,105 | 2,546 |
| 11 | 53 | 13 | 9 | 7 | 11 | 43 |
| 12 | 36 | 18 | 261 | 794 | 670 | 670 |
| 13 | 110 | 112 | 34 | 502 | 42 | 130 |
| 14 | 3 | 33 | 79 | 3 | 36 | 54 |
| 15 | 26 | 463 | 121 | 1,062 | 453 | 442 |
| 16 | 4,021 | 920 | 396 | 31 | 14 | 446 |
| 17 | 4 | 3 | 7 | 34 | 75 | 9 |
| 18 | 6 | 4 | 2 | 2 | 2 | 2 |
| 19 | 1,102 | 619 | 500 | 1,576 | 1,195 | 2,766 |

## Appendix C

### FIT FACTOR BY SUBJECT AND EXERCISE FOR THE 14 EEBD

| | | | Exercise | | | |
|---|---|---|---|---|---|---|
| Subject | NB | DB | SS | UD | RP | FG |
| 1 | 26 | 47 | 46 | 74 | 63 | 26 |
| 2 | 31 | 140 | 609 | 484 | 1,292 | 2,421 |
| 3 | 4,727 | 192 | 1,296 | 301 | 1,205 | 808 |
| 4 | 17 | 22 | 20 | 38 | 19 | 35 |
| 5 | 20 | 26 | 16 | 16 | 14 | 11 |
| 6 | 74 | 78 | 61 | 29 | 23 | 129 |
| 7 | 1 | 1 | 2 | 1 | 7 | 3 |
| 8 | 2 | 4 | 2 | 4 | 7 | 6 |
| 9 | 89 | 15 | 7 | 23 | 6 | 15 |
| 10 | 1,353 | 4,089 | 258 | 5,196 | 5,838 | 248 |
| 11 | 14 | 33 | 11 | 7 | 36 | 7 |
| 12 | 994 | 2,394 | 1,316 | 1,069 | 1,154 | 1,370 |
| 13 | 1,500 | 10,189 | 17,075 | 14,172 | 3,869 | 2,373 |
| 14 | 12 | 115 | 39 | 78 | 61 | 157 |
| 15 | 17 | 1,011 | 157 | 930 | 484 | 1,114 |
| 16 | 1,117 | 919 | 641 | 1,196 | 332 | 532 |
| 17 | 135 | 218 | 644 | 60 | 571 | 2,123 |
| 18 | 142 | 296 | 23 | 70 | 32 | 23 |
| 19 | 1,579 | 2,429 | 2,725 | 4,198 | 2,369 | 1,714 |

## Appendix D

### FIT FACTOR BY SUBJECT AND EXERCISE FOR THE FIREFIGHTER MASK

| Subject | NB | DB | Exercise SS | UD | RP | FG |
|---|---|---|---|---|---|---|
| 1 | 153 | 73 | 372 | 131 | 239 | 744 |
| 2 | 3 | 2 | 2 | 2 | 29 | 16 |
| 3 | 1,576 | 177 | 679 | 1,398 | 208 | 328 |
| 4 | 9 | 5 | 9 | 18 | 8 | 5 |
| 5 | 15 | 20 | 12 | 19 | 16 | 15 |
| 6 | 21 | 16 | 19 | 19 | 66 | 30 |
| 7 | 11 | 9 | 11 | 19 | 26 | 19 |
| 8 | 9 | 16 | 21 | 12 | 10 | 27 |
| 9 | 67 | 399 | 853 | 337 | 1,156 | 2,124 |
| 10 | 19 | 12 | 11 | 10 | 11 | 9 |
| 11 | 49 | 14 | 64 | 13 | 496 | 17 |
| 12 | 8 | 14 | 1 | 1 | 11 | 5 |
| 13 | 1,146 | 1,378 | 795 | 1,081 | 846 | 580 |
| 14 | 10 | 16 | 26 | 15 | 38 | 22 |
| 15 | 1 | 1 | 3 | 4 | 5 | 2 |
| 16 | 9 | 7 | 5 | 1 | 5 | 1 |
| 17 | 6 | 4 | 2 | 2 | 2 | 2 |
| 18 | 26 | 142 | 136 | 18 | 35 | 31 |
| 19 | 66 | 782 | 258 | 162 | 1,047 | 120 |

## Appendix E

## 11 EEBD RESULTS SCATTERPLOT DIAGRAMS FOR PROTOCOL EXERCISES

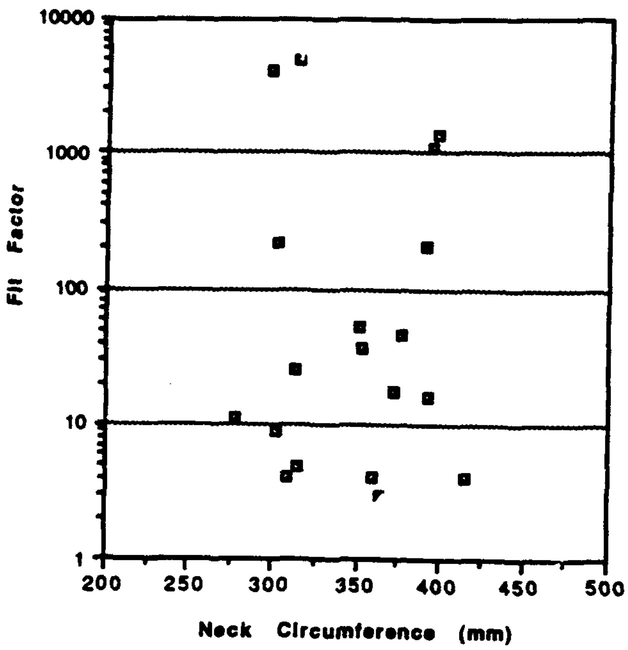


Figure E-1. 11 EEBD fit factor versus neck circumference for the normal breathing exercise.

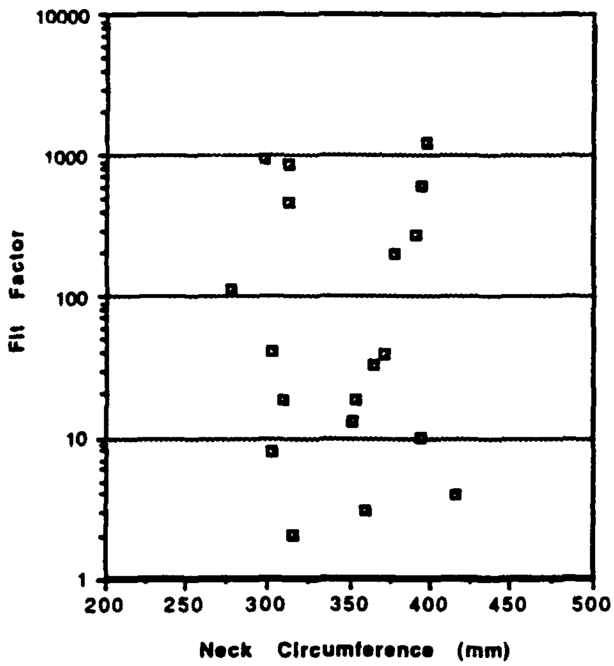


Figure E-2. 11 EEBD fit factor versus neck circumference for the deep breathing exercise.

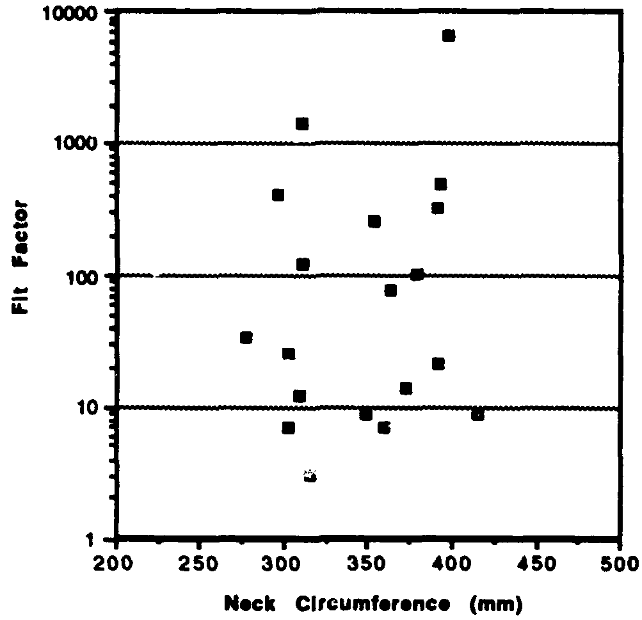


Figure E-3. 11 EEBD fit factor versus neck circumference for the head side-to-side exercise.

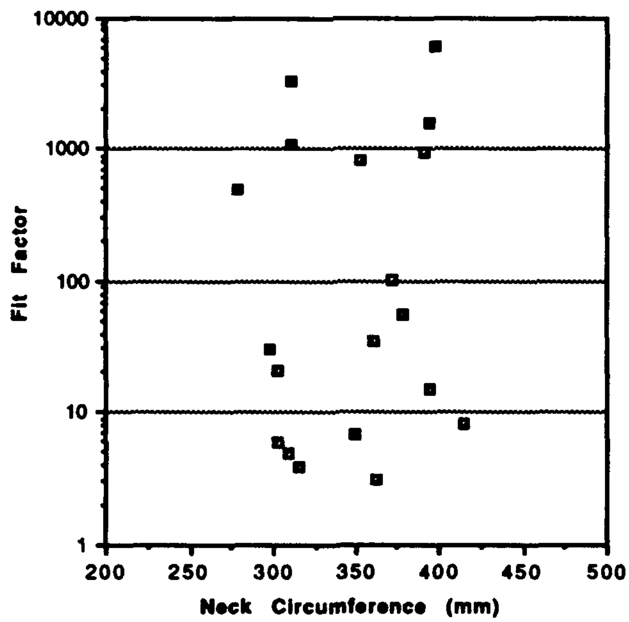


Figure E-4. 11 EEBD fit factor versus neck circumference for the head up-and-down exercise.

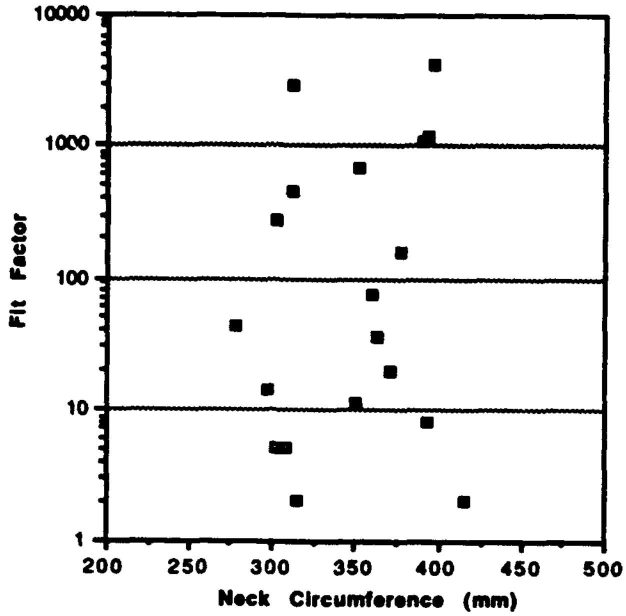


Figure E-5. 11 EEBD fit factor versus neck circumference for the read the paragraph exercise.

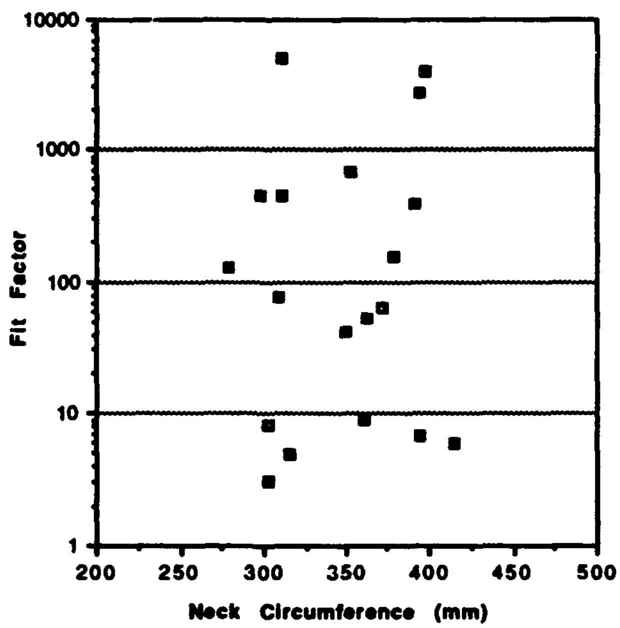


Figure E-6. 11 EEBD fit factor versus neck circumference for the facial grimacing exercise.

## Appendix F

## 14 EEBD RESULTS SCATTERPLOT DIAGRAMS FOR PROTOCOL EXERCISES

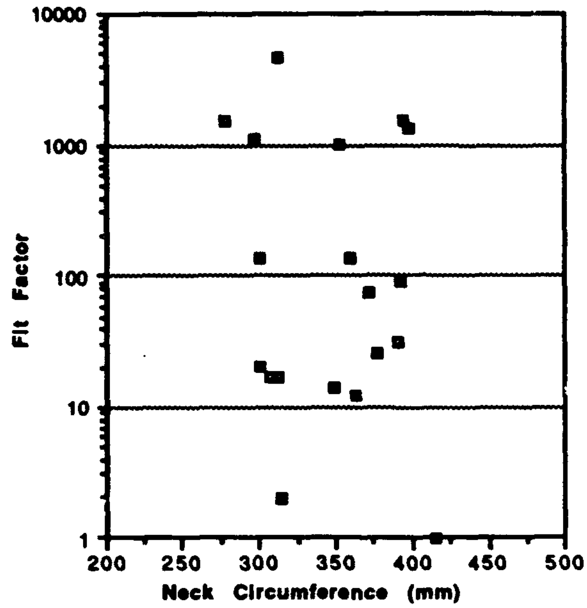


Figure F-1. 14 EEBD fit factor versus neck circumference for normal breathing exercise.

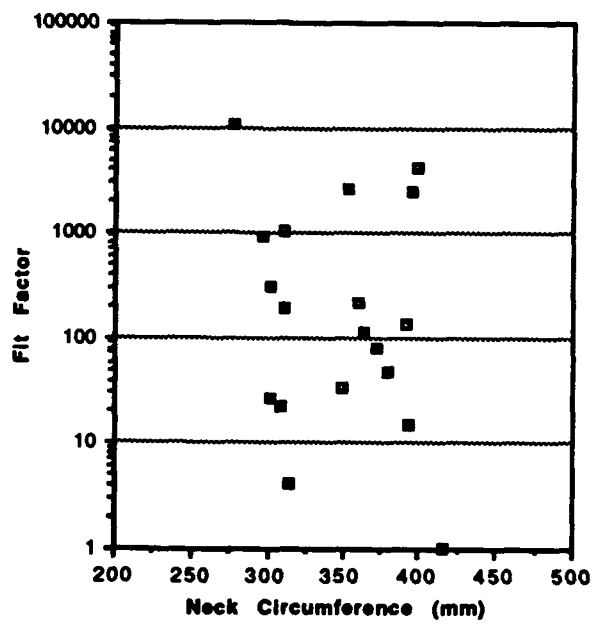


Figure F-2. 14 EEBD fit factor versus neck circumference for the deep breathing exercise.

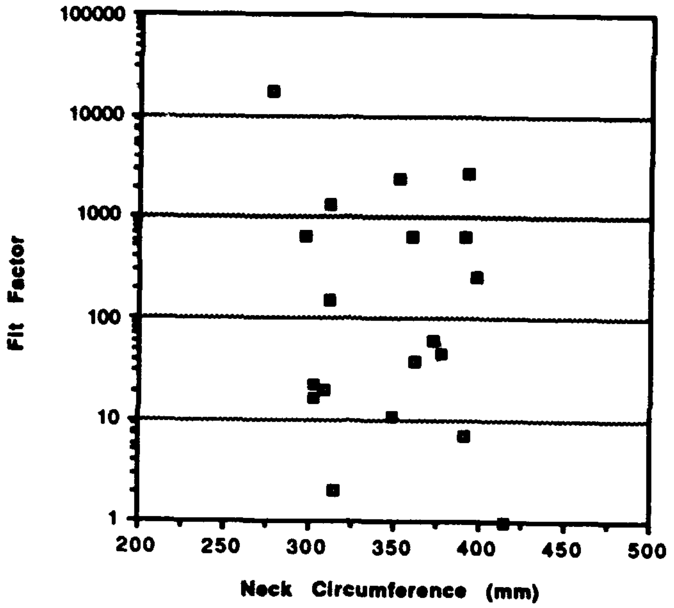


Figure F-3. 14 EEBD fit factor versus neck circumference for the head side-to-side exercise.

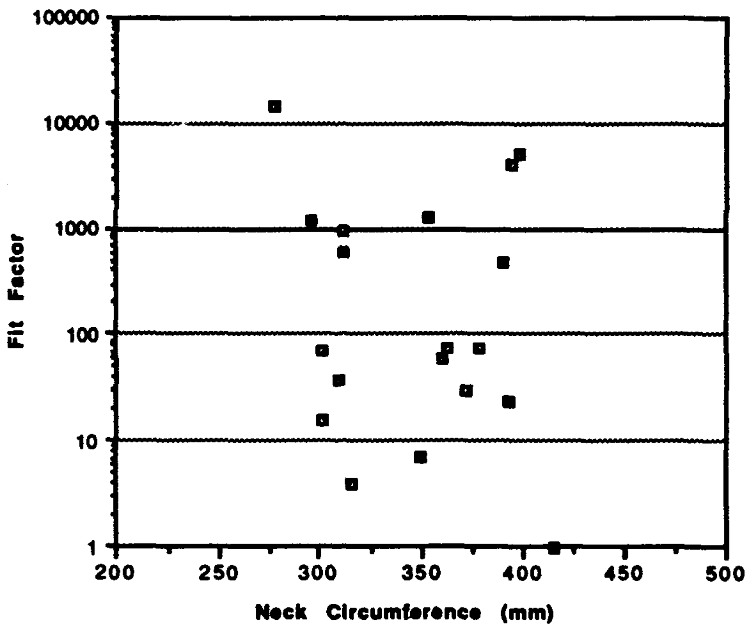


Figure F-4. 14 EEBD fit factor versus neck circumference for the head up-and-down exercise.

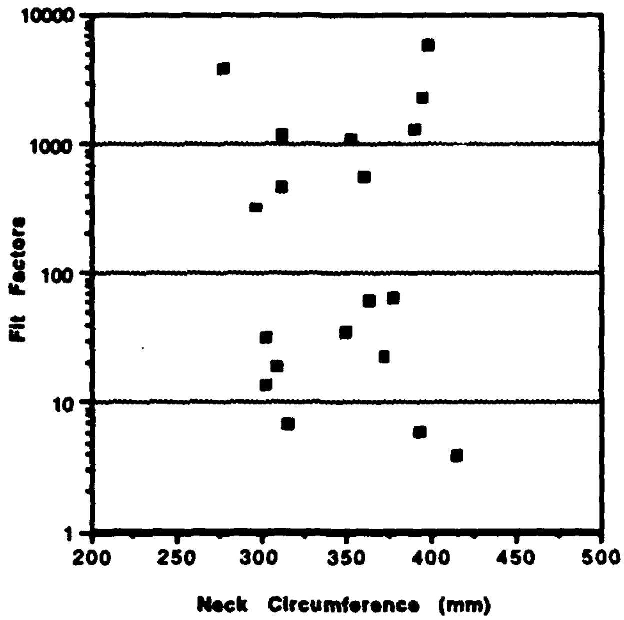


Figure F-5. 14 EEBD fit factor versus neck circumference for the read the paragraph exercise.

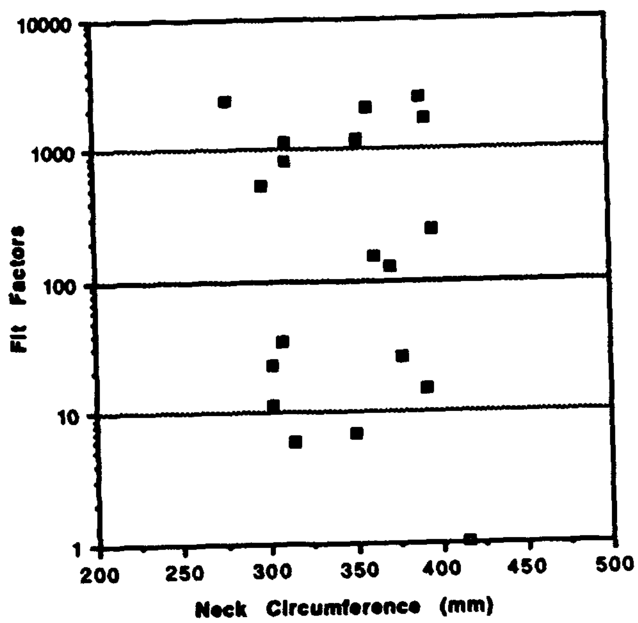


Figure F-6. 14 EEBD fit factor versus neck circumference for the facial grimacing exercise.